DIII–D RESEARCH PROGRAM

DIII–D Mission: to establish the scientific basis for the optimization of the tokamak approach to fusion energy production

by
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FY05 Budget Planning Meeting
Washington, DC

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GENERAL ATOMICS

054-03/TST/jy

THE DIII–D RESEARCH PROGRAM FOCUSES ON KEY AREAS FOR THE FUTURE

- **Advanced Tokamak: in-principle steady-state, high performance discharges**
  - Scientific understanding of key elements
    - ★ MHD stabilization
    - ★ Profile optimization
  - Plasma control
  - Integrated self-consistent scenarios

High average power
⇒ ITER
⇒ CTF
⇒ Power plant

- **Transport: major advance in turbulent transport understanding and control**
  - State-of-the-art predictive simulations
  - Measure turbulence generated flows and short wavelength turbulence

A grand challenge in plasma science

- **Mass transport in the boundary**
  - Measure flows, erosion and redeposition
  - Measure ELM effects
  - Integrated modeling of the boundary

Key R&D for ITER
⇒ Tritium retention

DIII–D progress over a broad range of science issues will support these accomplishments

HARDWARE IMPOVEMENTS ARE NEEDED TO DEVELOP STATE OF THE ART PHYSICS

Physics Element	Key Hardware Improvements Needed
• **Advanced tokamak**	
— RWM, stabilization	I–coil/controllers, High bandwidth actuators
— NTM stabilization	ECCD (6 MW)
— Control of J(ρ)	ECCD (6 MW) FWCD (3 MW)
	ECCD (9 MW, 10 s), FWCD (6 MW, 10 s)
— Density control/shape	High δ pumped divertor, pellets
— Control of P (ρ)	EC, FW, Cntr NBI (future)
— Long pulse (10 s)	Substation, beltbus and diodes
• **Transport**	
— Rotation, $\omega_{E\times B}$, α-stab.	EC, FW, I–coil Cntr NBI (future)
— Electron transport	Modulated ECH, high k turbulence diagnostics
— Zonal flows	Advanced multifluid 2–D BES
— Code implementation	Massively parallel computers (future)
• **Boundary**	
— Flows	Divertor DNB, divertor CER
— Erosion, redeposition	Quartz micro-balance

DIII–D FOCUS AREAS SUPPORT PROGRESS IN FOUR FUSION PROGRAM THRUSTS

- **Advanced Tokamak: in-principle steady-state, high performance discharges**
  - Scientific understanding of key elements
    - ★ MHD stabilization
    - ★ Profile optimization
  - Plasma control
  - Integrated self-consistent scenarios

Configuration optimization
Burning plasmas
Fundamental understanding
Enabling (control) technology

- **Transport: major advance in turbulent transport understanding and control**
  - State-of-the-art predictive simulations
  - Measure turbulence generated flows and short wavelength turbulence

Fundamental understanding

- **Mass transport in the boundary**
  - Measure flows, erosion and redeposition
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Burning plasmas
Fundamental understanding

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DIII–D FOCUSED EFFORTS SUPPORT THE FESAC/IPPA GOALS

- **Advanced Tokamak: in-principle steady-state, high performance discharges**
  - Scientific understanding of key elements
    - ★ MHD stabilization
    - ★ Profile optimization
  - Plasma control
  - Integrated self-consistent scenarios

Integration and optimization High performance 3.3 Science 3.1 Configuration 3.2 **Profile control** 3.3.1, 3.1.3 **High beta & disruptions** 3.3.2, 3.1.2 **Density control** 3.3.1, 3.1.4 **Enabling (control) technologies** 3.4.1	

- **Transport: major advance in turbulent transport understanding and control**
  - State-of-the-art predictive simulations
  - Measure turbulence generated flows and short wavelength turbulence

Turbulence and transport 3.1.1

- **Mass transport in the boundary**
  - Measure flows, erosion and redeposition
  - Measure ELM effects
  - Integrated modeling of the boundary

Burning plasmas 3.3.3
Boundary science 3.1.4

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ADVANCED TOKAMAK RESEARCH ON DIII–D

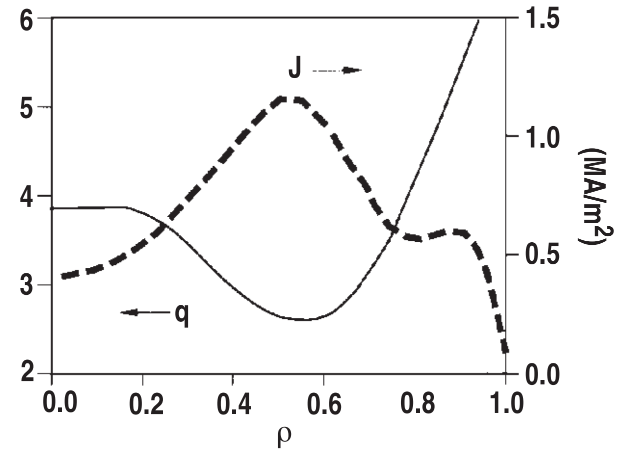
Realizing the Ultimate Potential of the Tokamak

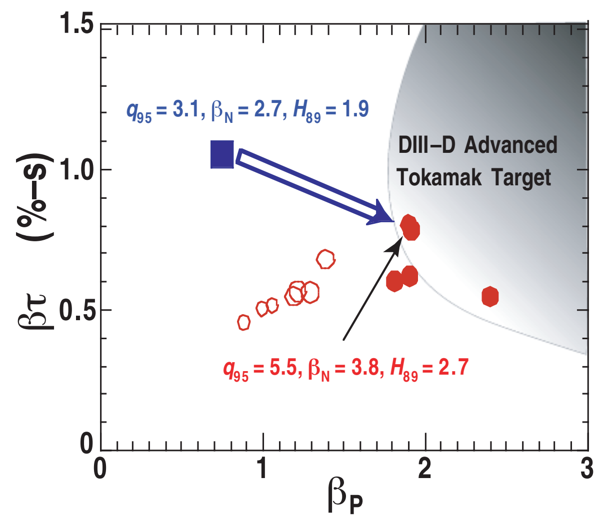
Making fusion energy attractive

- Steady state
  - With low recirculation power $\Rightarrow$ high β_P (self-generated bootstrap current)
- High power density $\Rightarrow$ high β_T
- High energy gain
  - $\Rightarrow$ High β_P, β_N
  - At reduced B_T, I_p $\Rightarrow$ high τ_E, H

...all simultaneously integrated

- Self consistent optimization
  - plasma shape
  - plasma profiles
  - MHD stabilization





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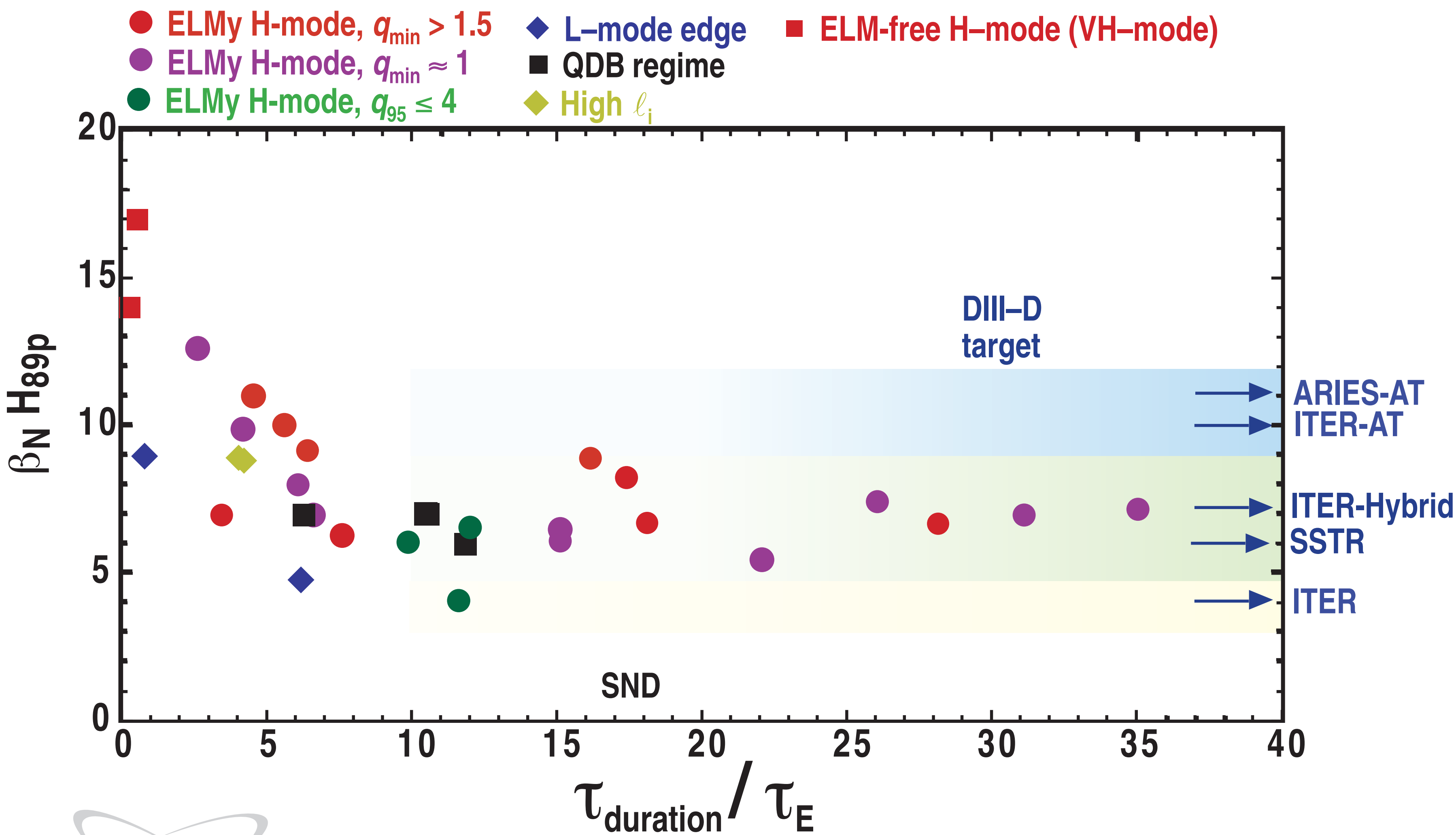
AT PLANS FOR 2004 AND 2005

The building blocks for AT are in place
Major emphasis in 2004 and 2005 are integration and optimization

- First begin integration and optimization in SND discharges, τ_{dur} ~ 5 s
  Density control proven in SND and profile control demonstration has started
  - Increase performance – raise beta
    Wall stabilization (with and without rotation)
  - Increase non-inductive current to 100%
    - ★ Increase driven current
      - P_{EC} – increase power and duration
      - Operate FW, increase P_{FW}
        Higher Te and βe to increase current drive efficiency
        Control q(0) and central magnetic shear
    - ★ increase bootstrap, βp, βn
- Extend duration and optimize performance in DND, τ_{dur} ~ 10 s
  Significant increase in achievable beta
  - Increase off-axis CD
    - ★ P_{EC} and P_{FW}, increase power and duration
    - ★ Key challenge is density control
      Add lower higher triangularity pumped divertor

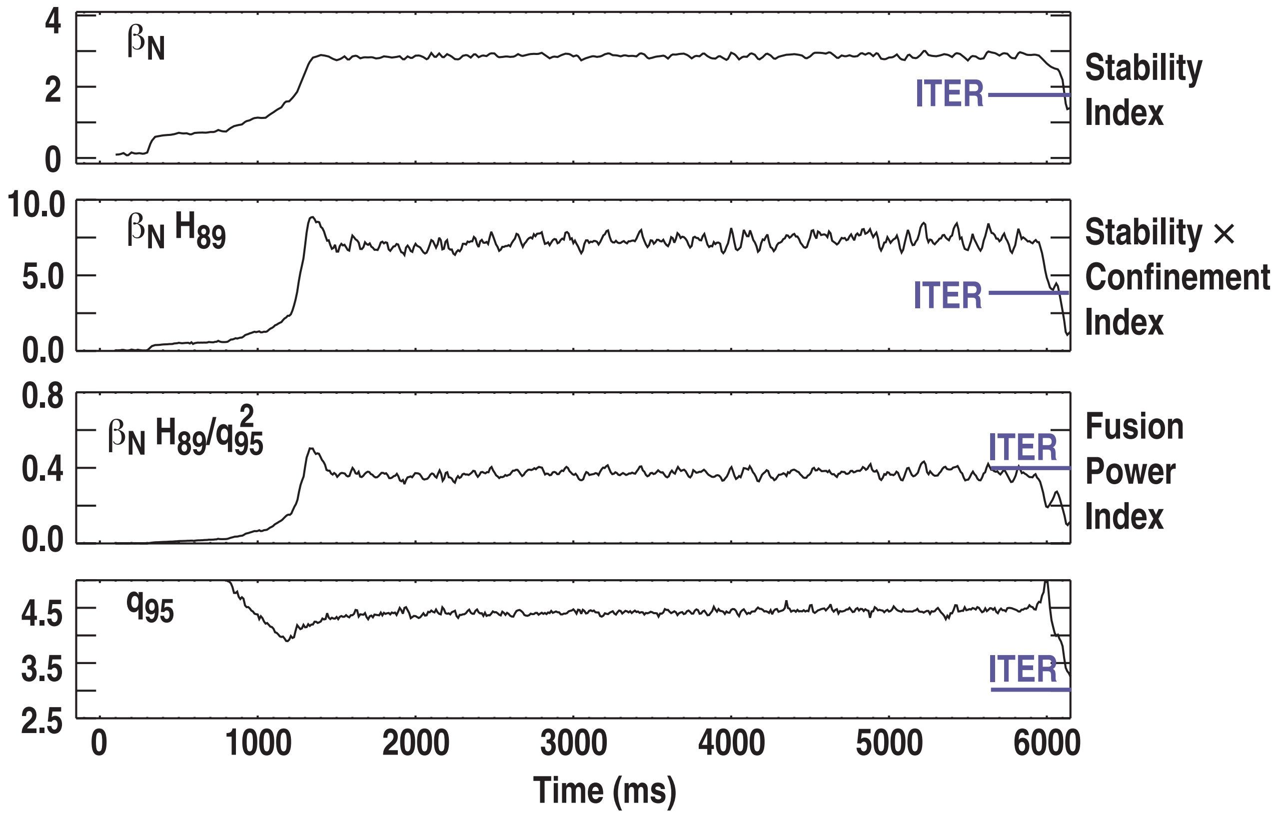
SIGNIFICANT PROGRESS TOWARD LONG-PULSE HIGH PERFORMANCE

- Advanced performance found in many operating regimes



DIII–D STEADY STATE AT SCENARIOS AND STATIONARY "hybrid" SCENARIOS ARE DEVELOPING THE BASIS FOR ITER LONG PULSE DISCHARGES (≳ 4000s, ~500 MW)

Stationary hybrid scenario, q_{95} = 4.5 (104205)



- Stabilize NTM to increase performance (β)
  - Off-axis ECCD
- Increase confidence in extrapolation to ITER
  - Joint experiments with IEA/ITPA
  - $T_e/T_i \rightarrow 1$ (P_{EC}, P_{FW})

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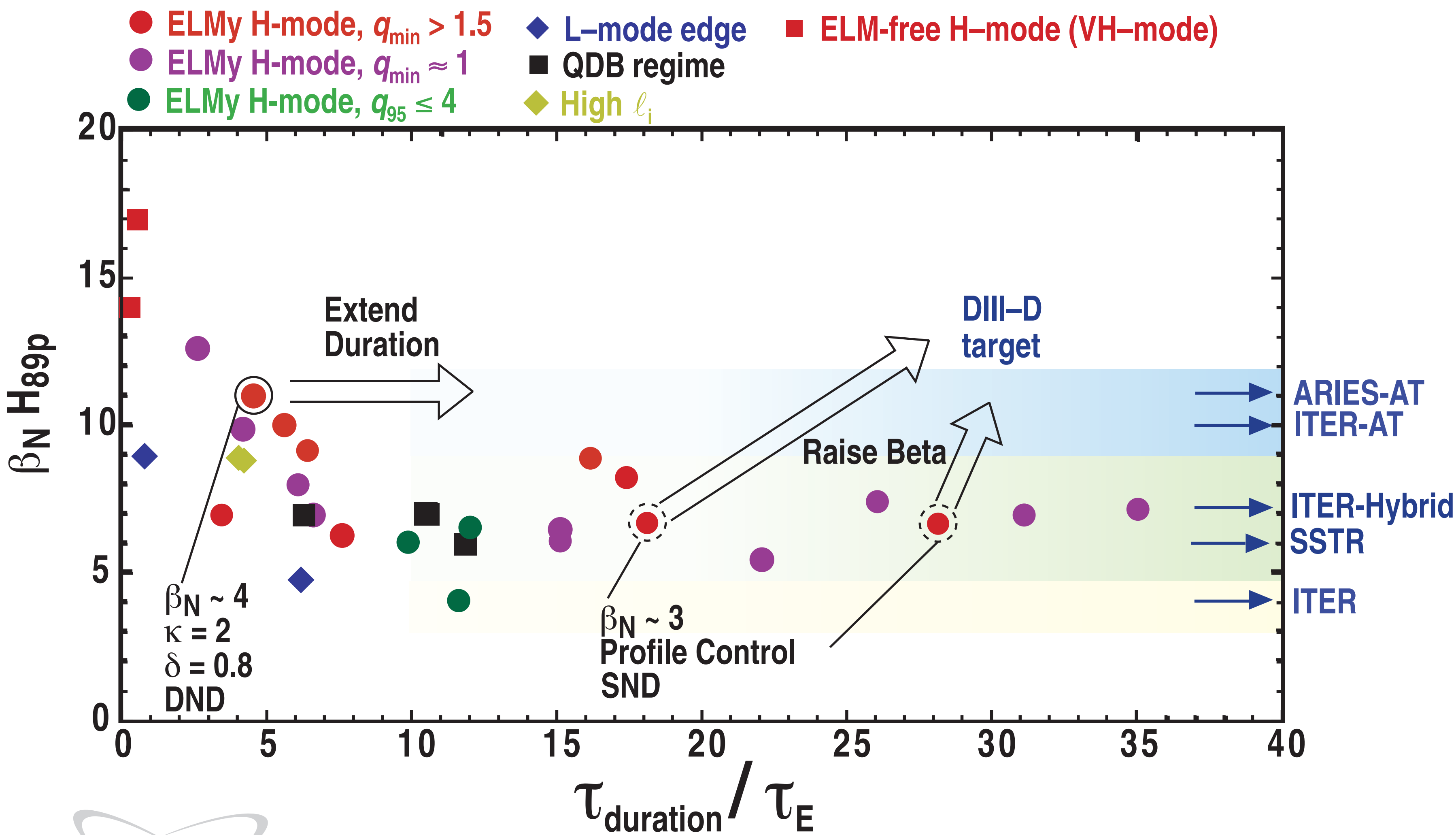

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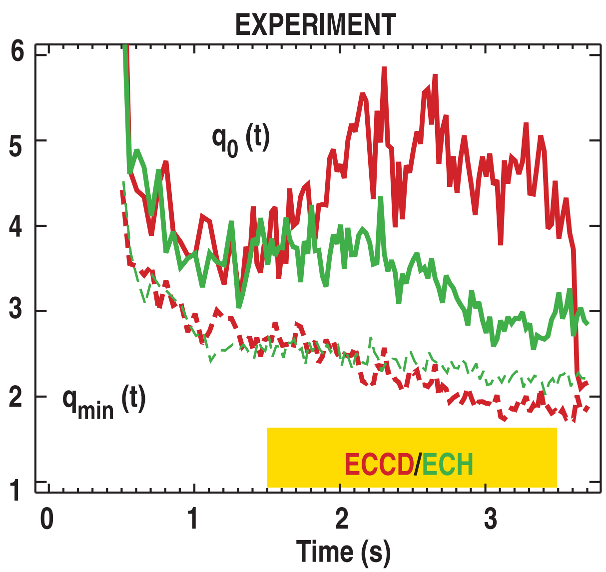
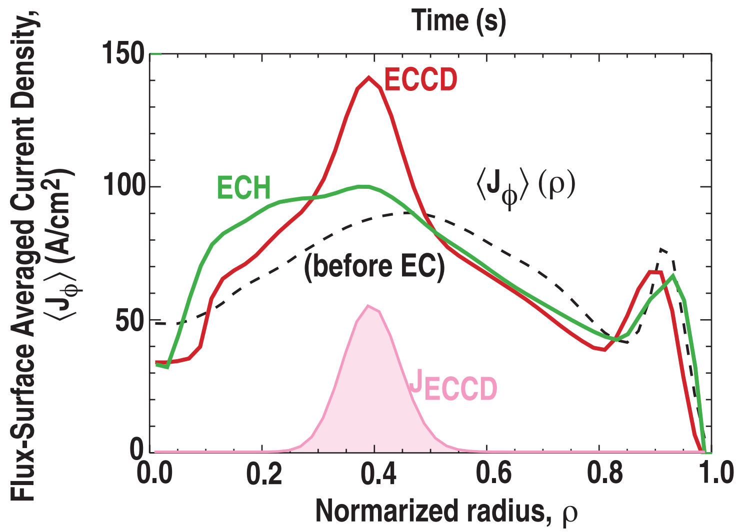
CLEAR DEMONSTRATION OF CURRENT PROFILE MODIFICATION BY ECCD IN HIGH PERFORMANCE PLASMAS

- $\beta_N = 2.8 \sim \beta_N^{\text{no wall}}$





High Bootstrap Fraction AT

I_p	1.2 MA		B_T	1.85 T
ECCD	0.13 MA	10%	EC	2.5 MW
NBCD		30%	NB	8 MW
Bootstrap		53%	β_T	3.1%
Ohmic		7%	β_N	2.8
Non-Inductive		93%	H	2.5
			β_NH	7

Tools needed to raise beta for long pulse

- RWM stabilization
  - high triangularity pumped DND
- 6 MW EC system → 9 MW
- 3 MW FW system → 6 MW
- Upgraded transformer for heating systems

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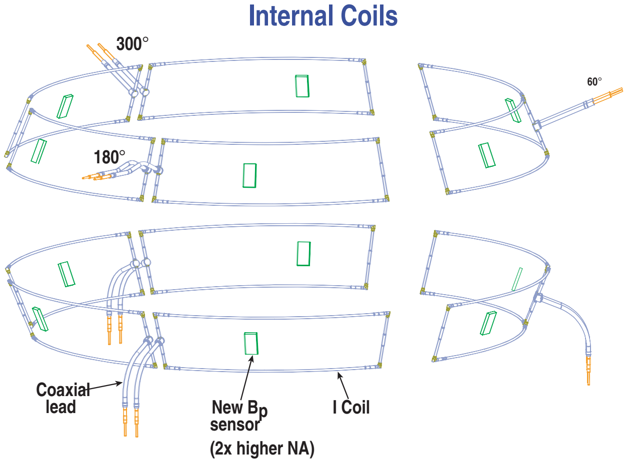
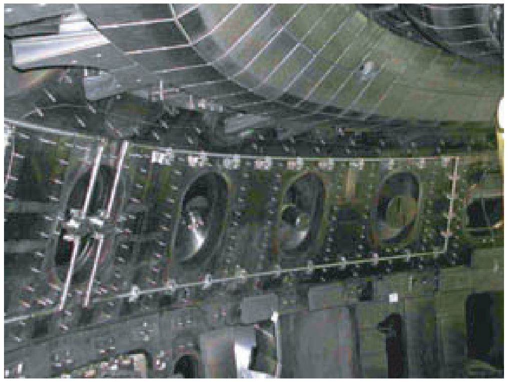
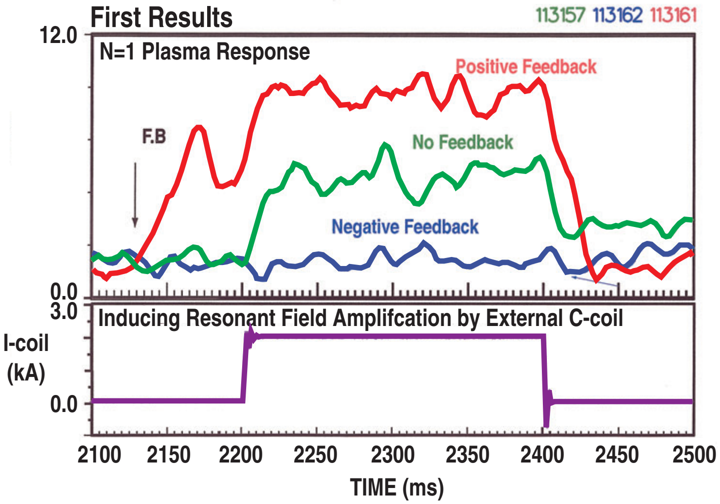
NEWLY INSTALLED INTERNAL CONTROL COILS: AN EFFECTIVE TOOL FOR ACTIVE AND PASSIVE STABILIZATION OF THE RWM

- Highly collaborative (General Atomics, Columbia, Princeton)
- Key relevance to ITER, FIRE, CTF, and other magnetic configuration (ST, RFP...)
- Passive feedback: better matching to error field spectrum ⇒ $\beta_N > \beta_N^{\text{no wall}}$ with rotation
- Active feedback: $\beta_N > \beta_N^{\text{no wall}}$ without rotation, (high bandwidth actuators)
- Operation with plasmas just beginning ⇒ Demonstrated RWM Feedback







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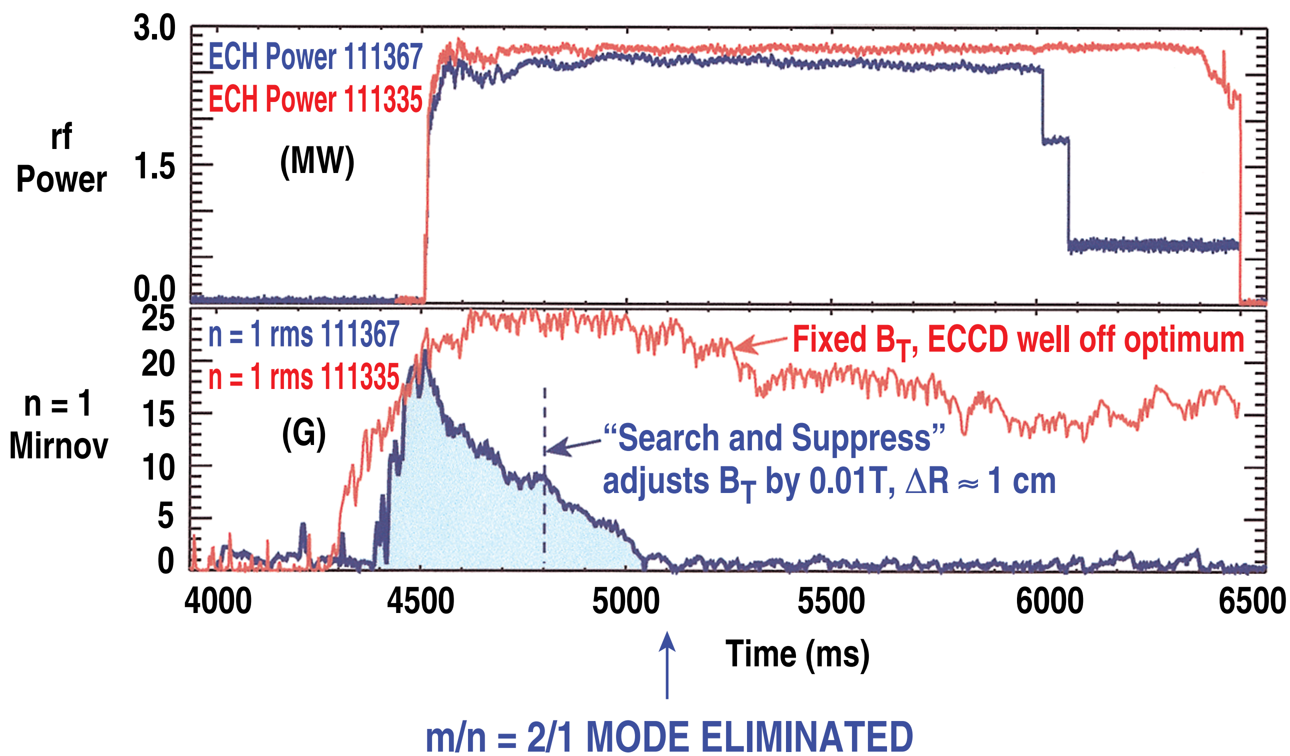
FEEDBACK STABILIZATION OF NTMs WITH LOCALIZED ECCD WORKS

- m/n = 3/2, 2/1, NTM completely stabilized with ECCD



- Future work
  - optimize feedback algorithms
  - increase beta

    ⇒ Increased ECCD pulse length and power

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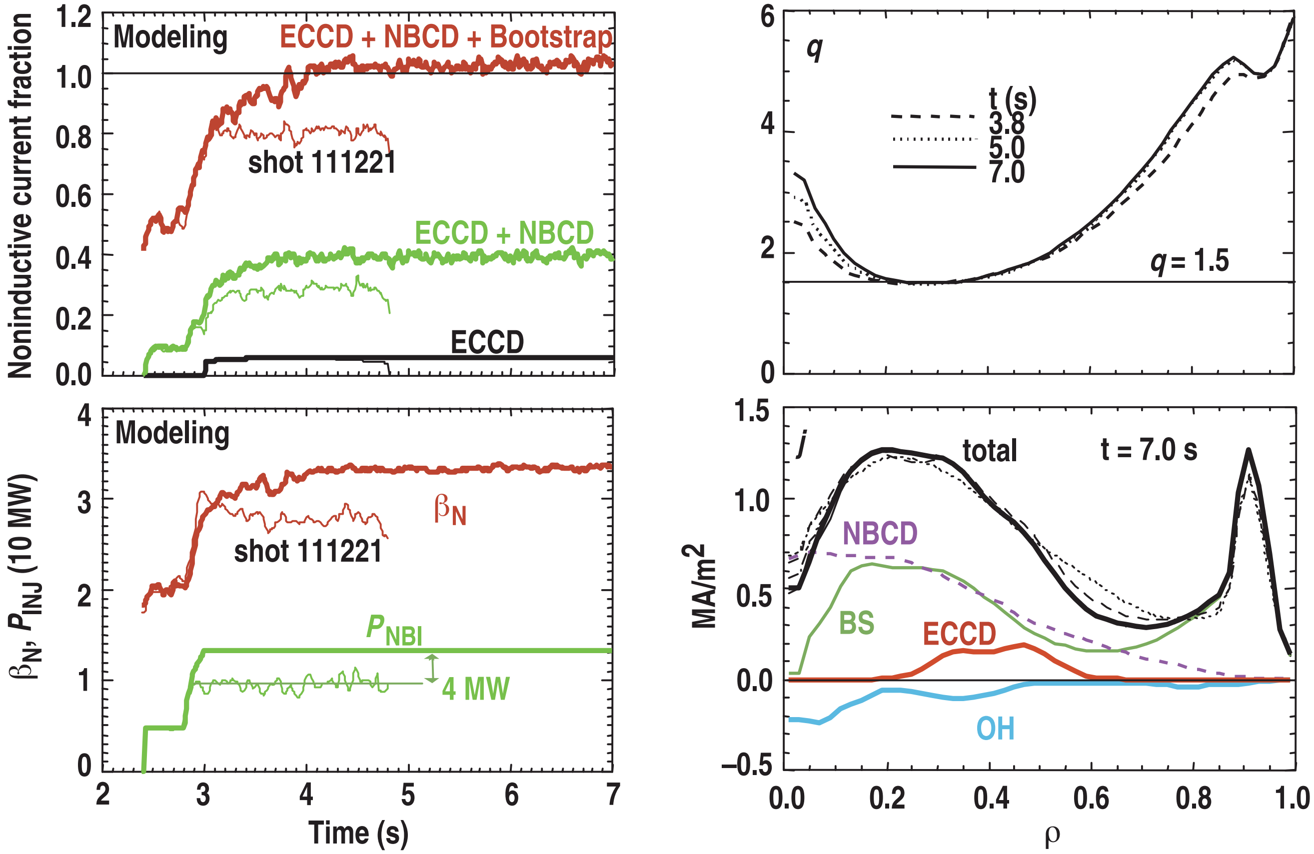
MODELING PREDICTS EXISTING DISCHARGES CAN BE EXTENDED TO 100% NONINDUCTIVE WITH NEAR TERM HARDWARE CAPABILITIES



Highlights need for

- RWM stabilization
- Longer pulse EC
- FW operation

- Increase Bootstrap current
  - β_p, β_N
  - $\beta_N \gtrsim \beta_N^{\text{no wall}}$
- Increase driven current
  - P_{NBI}
  - P_{EC} (2.5 MW) (2-4 s in 2003)

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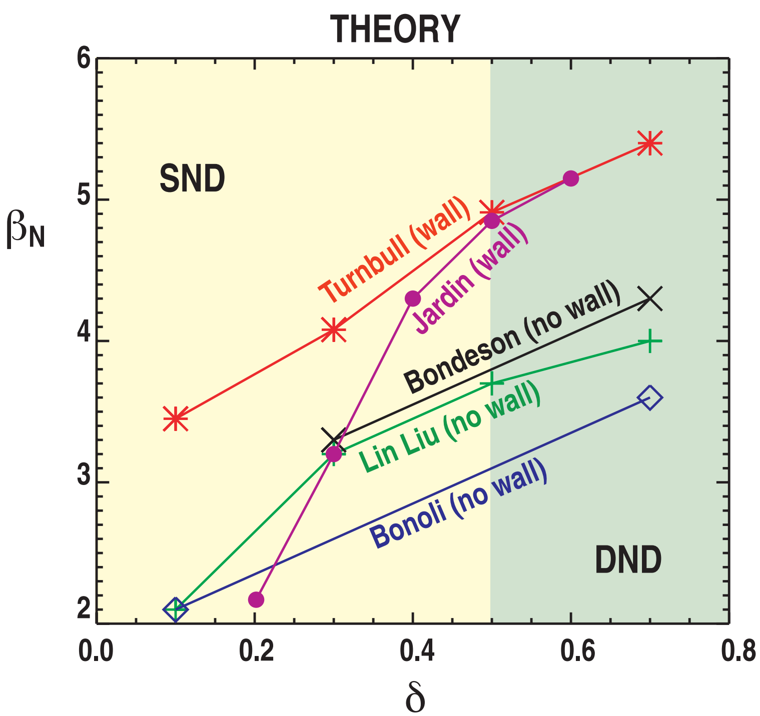
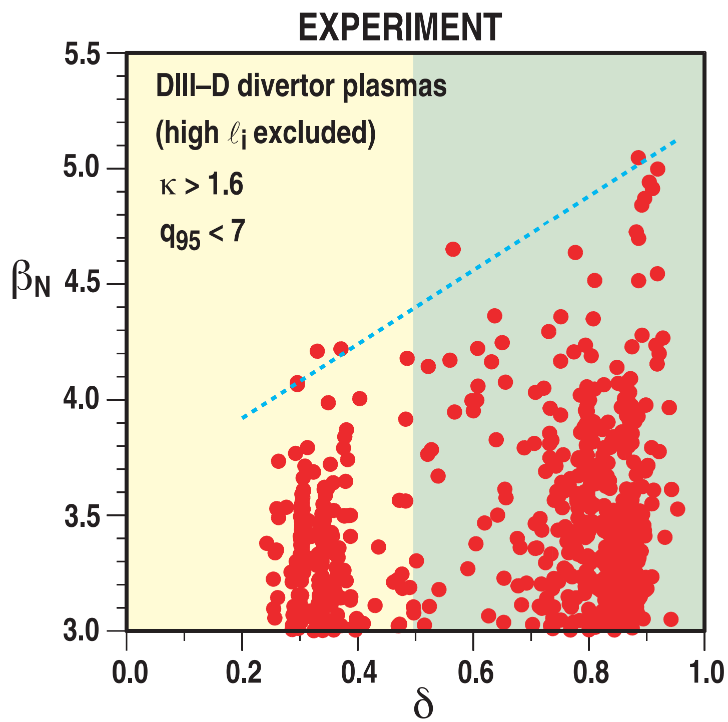
HIGH BETA FAVORS STRONG SHAPING AND DND OPERATION

- Maximum achievable normalized Beta increses with shaping





- Broadening the pressure profile enhances the shape dependence

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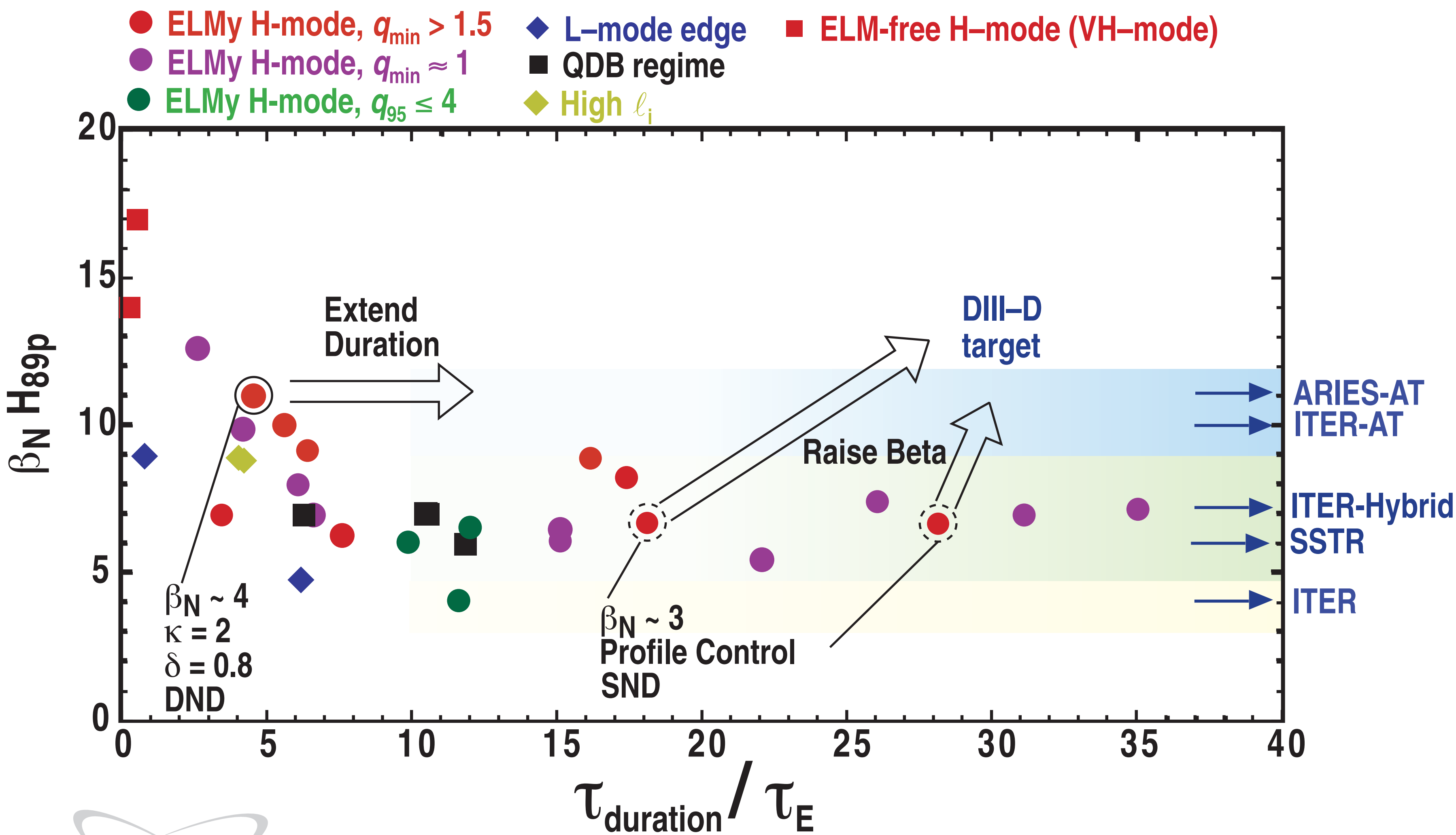
SIGNIFICANT PROGRESS TOWARD LONG-PULSE HIGH PERFORMANCE

- Advanced performance found in many operating regimes



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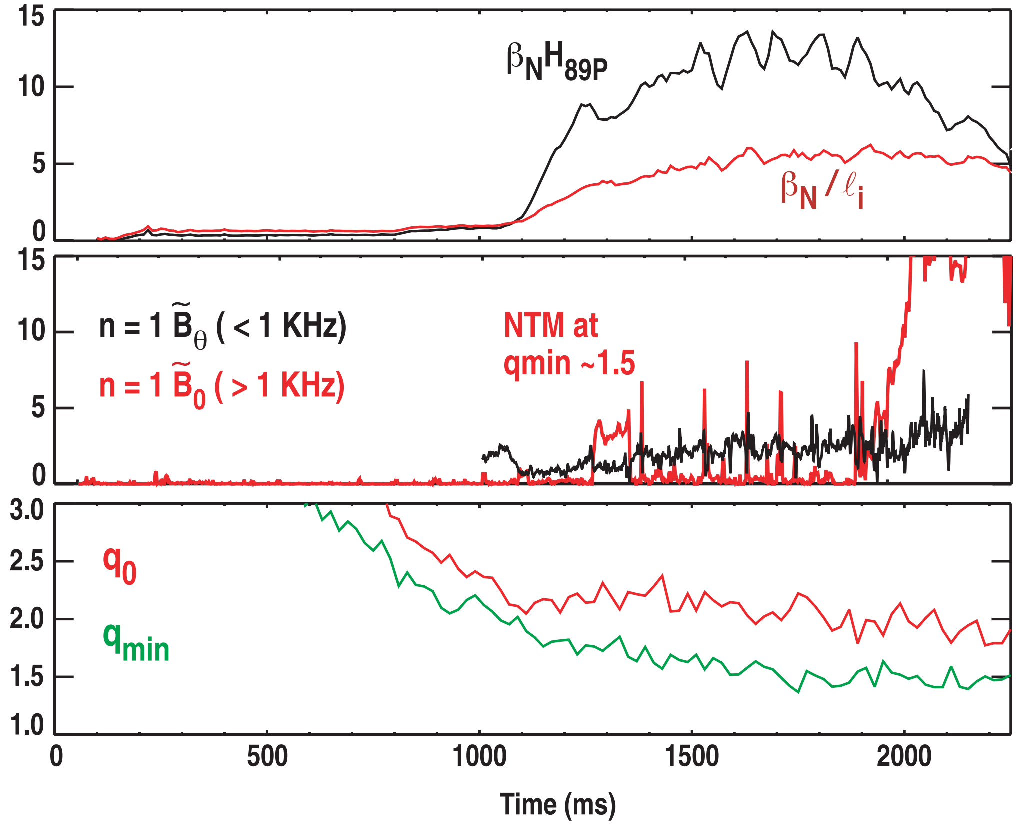
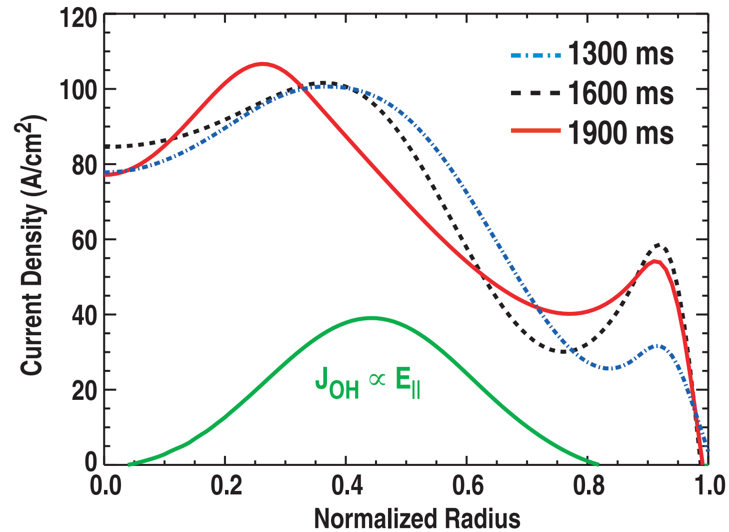
DENSITY CONTROL AND CURRENT PROFILE CONTROL ARE NEEDED TO EXTEND HIGH PERFORMANCE DISCHARGE

$\beta_N \approx 4$, $H_{89P} \approx 3$ $\beta_p \approx 2$





- $\beta_N > \beta_N^{no\ wall}$, RWM stabilized by rotation

Tools needed to extend duration

- Density control
  - — high triangularity pumped DND
- 6 MW EC system → 9 MW
- 3 MW FW system → 6 MW
- Upgraded transformer for heating systems

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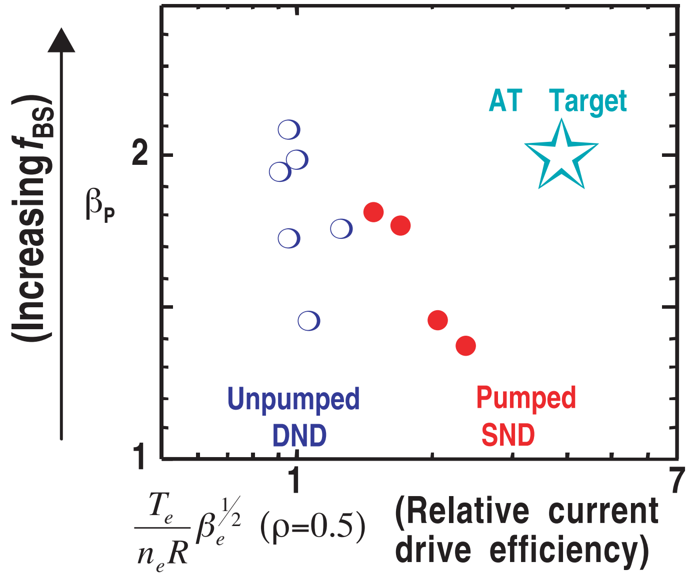
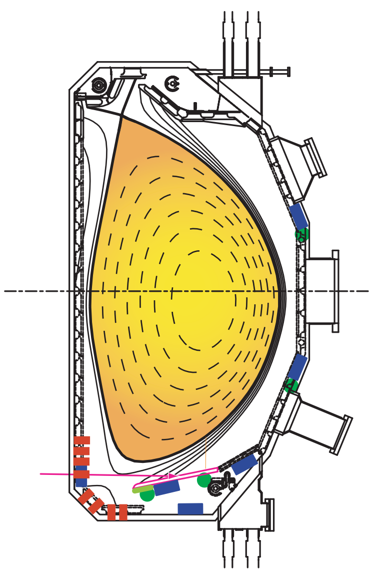
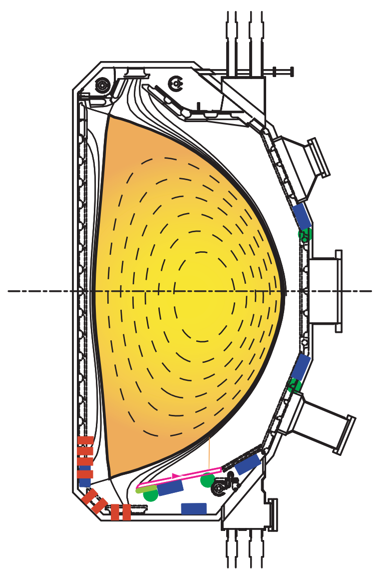
DENSITY CONTROL IS REQUIRED FOR SUSTAINING *AT*







- **Steady state requires additional current approximately at the half radius**
  - Bootstrap
  - Off-axis current drive (ECCD)
- **Density control improves current drive efficiency**
  - Density control adequate in SND configuation
  - Improved density control needed for long pulse DND
- **Our plan is to optimize AT solutions for both SND and DND configurations**

⇒ ***Add lower high triangularity divertor pump***

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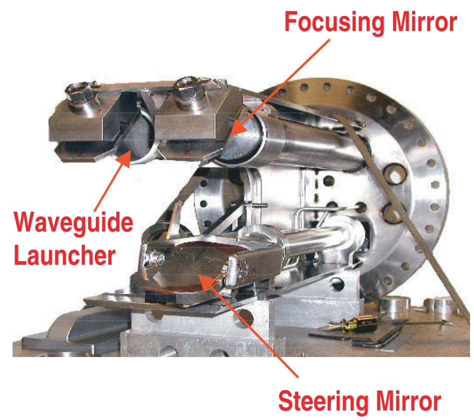
LONGER PULSE WITH INCREASED HEATING POWER REQUIRE AN UPGRADED HIGH VOLTAGE SUBSTATION AND MINOR TOKAMAK UPGRADES

Increased heating power

10 s, 1 MW CPI Gyrotron

EC Antenna (PPPL)



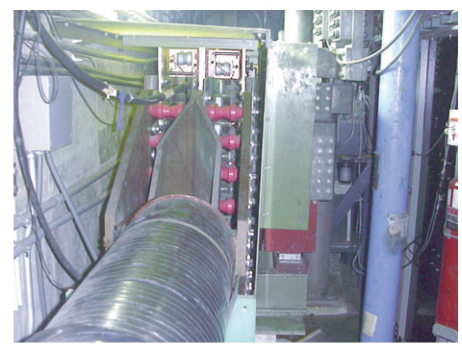
10 s, FW Antenna (ORNL)

Power Infrastructure

138 kV substation

Toroidal Coil Beltbus

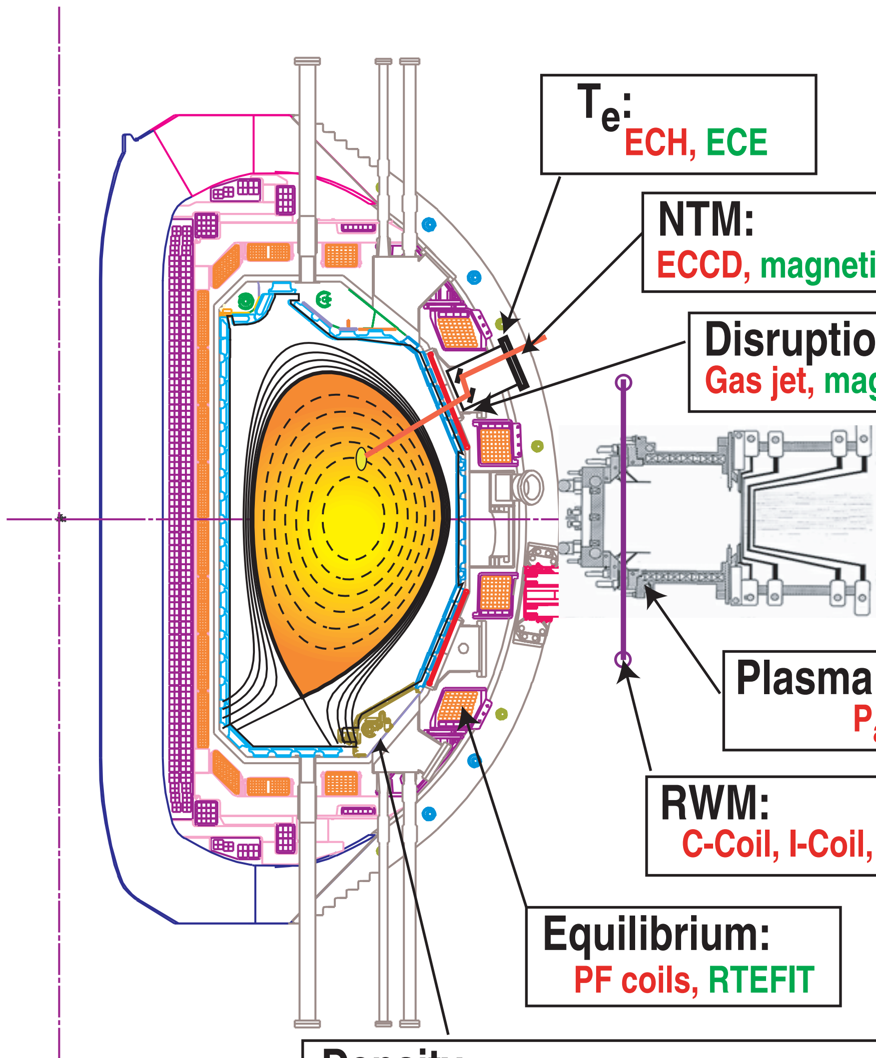
Toroidal Coil Freewheeling Diodes



A NEW ERA IN PLASMA CONTROL: KEY TO THE DIII–D AT PROGRAM

Real Time Feedback Controlled

(Actuator, Sensor)



Under Development

Integrated control:
Expanded PCS
Validated models

Current profile control:
ECCD/FWCD, MSE

Optimized RWM control:
I-Coil
Expanded magnetics

Disruption detection, correction, mitigation:
MHD regulation — PCS
Expanded magnetics

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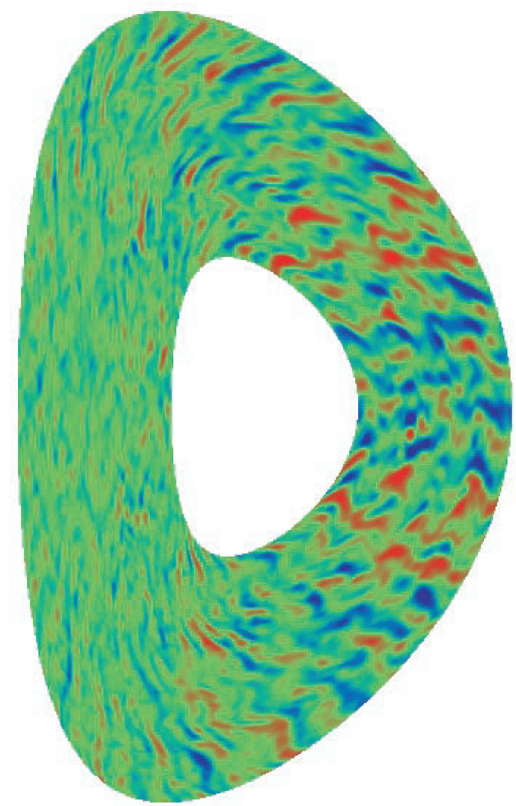
THE DIII–D PROGRAM PLANS A FOCUSED EFFORT ON UNDERSTANDING TURBULENT TRANSPORT TOWARD MEETING LONG RANGE IPPA GOALS

— As part of a community-wide effort, in concert with TTF —

- **Lead goal is predictive understanding of transport FESAC/IPPA goal 3.1.1**
  - Five-Year Objective: Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems

- **For the first time, codes contain essential physics needed for meaningful comparison with experiment**
  - Kinetic ions and electrons at finite beta
  - Complete two dimensional geometry
  - Finite gyroradius
  - Profile variation (q, T_e, T_i, $E \times B$ flow...)
  - Self consistent $E \times B$ shear flow



Fusion SciDAC Computing Initiative

⇒ New diagnostic measurements are essential for this comparison

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DIII–D TRANSPORT PROGRAM PLANS WILL ADDRESS KEY ELEMENTS IDENTIFIED IN THEORY AND MODELING

DIII–D goal: to play a lead role in a national effort to understand the basic physics processes by which plasma turbulence produces cross field transport and to use that knowledge to control transport

- Measure and understand short wavelength turbulence (election transport)
  - Far infrared scattering (UCLA)
  - Phase contrast imaging (MIT)
  - Microwave back scattering (proof of principle) (UCLA/UNM)
- Measure and characterize zonal flows
  - 2 Dimensional beam emission spectroscopy (WIS)
- Characterize and understand the edge pedestal
  - Key for optimizing burning plasma experiment (ITER)
- Investigate transport barrier physics ($\omega_{E\times B}$, α-stabilization)
- Strong partnership between theory/simulation and experiment is needed
  - State of the art simulation codes – computing cycles
  - "synthetic" diagnostic codes to make direct comparison with experiment
  - New diagnostic measurements
  - Plasma control tools

UNDERSTANDING MASS TRANSPORT IN THE PLASMA BOUNDARY: A KEY SCIENCE CHALLENGE, AND IMPORTANT ITER R&D

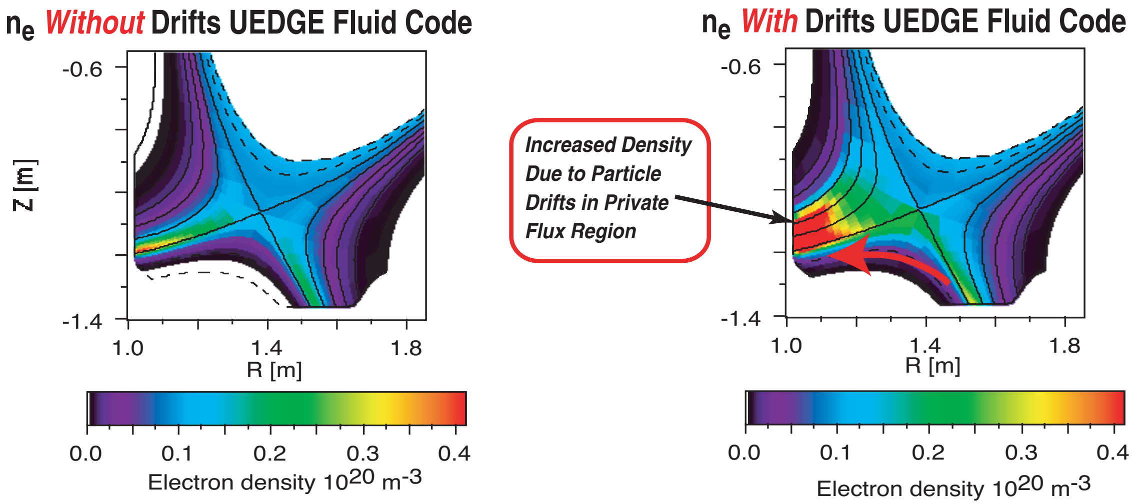
To qualify carbon PFCs for fusion systems

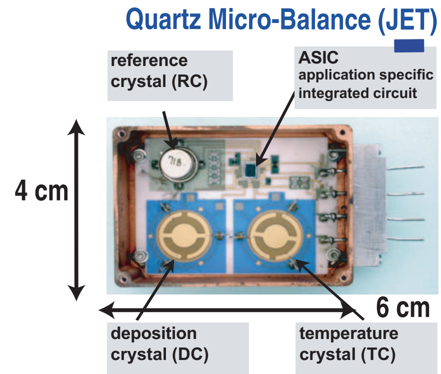
- Physics must show co-deposited material is in a predictable location
- Technology must develop a means to remove tritium from co-deposited layers

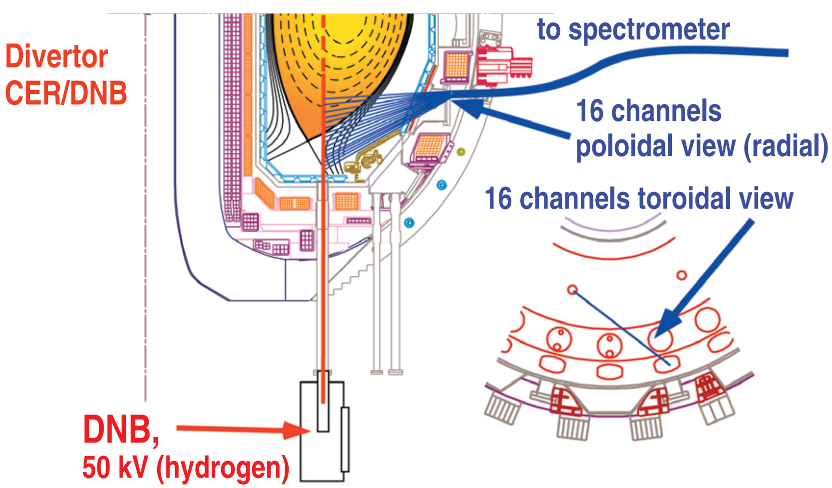
DIII–D Goal: Understand the physics of “mass transport” in the SOL, plasma chamber and develop techniques to affect and control the flows of particles around the boundary of divertor tokamak

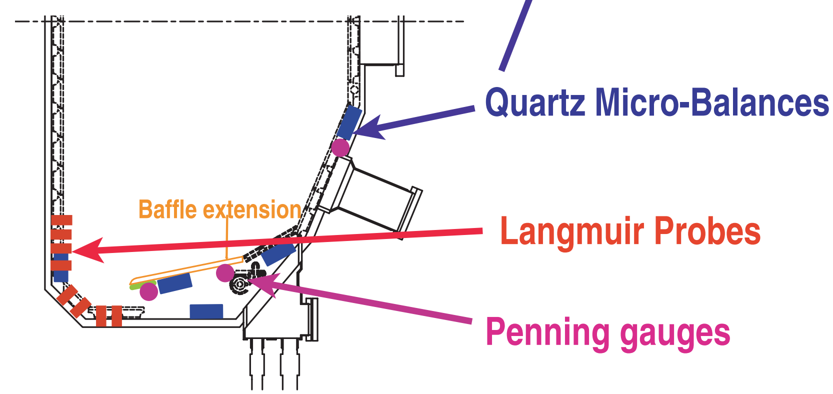
- Measure particle sources, sinks and flow channels
  - New diagnostics measurements are essential
- Measure erosion, redeposition
- Measure ELM effects
- Develop predictive capability of the boundary plasma
  - Integrated modeling, from the divertor plate to the top of the pedestal: impurities (DIVIMP), neutrals (EIRENE), SOL (UEDGE), edge turbulance (BOUT)

NEW MEASUREMENTS ARE KEY TO UNDERSTANDING MASS TRANSPORT IN THE PLASMA BOUNDARY AND ADDRESSING THE TRITIUM RETENTION ISSUE









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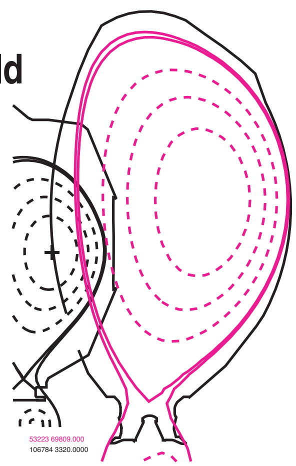
COLLABORATIVE EXPERIMENTS COORDINATED BY IEA/ITPA ENABLES PHYSICS VALIDATION IN SUPPORT OF ITER

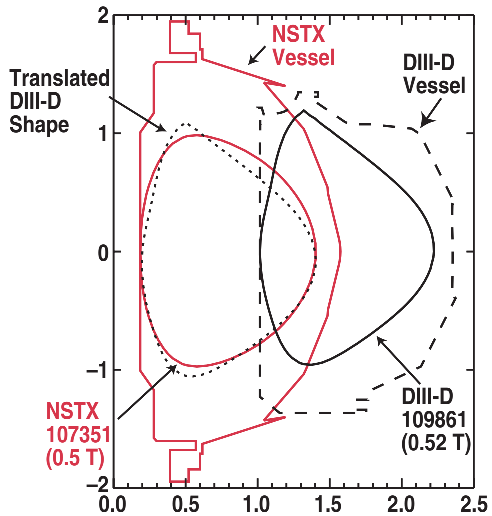
- Key mechanism to develop physics basis for next step
  Burning plasmas (ITER)

- National and International coordination through IEA/ITPA is working
  DIII–D FY2003 → 18 topics (23/53 days)

JET/DIII–D
NTM Threshold



NSTX/DIII–D Alfvén Instabilities



Planned collaborations

- JT-60U
  — Steady-state, high performance
- JET
  — AT/ITB, Hybrid scenrios
  — RWM and NTM
  — RF and rotation
  — Pedestal physics, QH-mode
  — Disruption mitigation
- ASDEX
  — RWM and NTM
  — Pedestal physics, QH-mode
  — Hybrid scenarios
- TCV
  — H–mode
- C-MOD
  — Pedestal
  — SOL
  — NTM
- NSTX
  — Alfven
  — Transport
- HBT-EP
  — RWM

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DIII–D PROGRAM ELEMENTS ARE AIMED AT INSURING THE SUCCESS OF AND GAINING THE GREATEST BENEFIT FROM ITER

AT

- Develop long pulse, high performance discharges for ITER
  - Hybrid scenarios
  - Full steady-state advanced tokamak
- Resistive wall modes
  - Detailed physics understanding
  - Feedback control
- Neoclassical tearing modes
  - Threshold; scaling
  - Stabilization
  - Avoidance
- Disruptions
  - Gas jet penetration, predictive models, scaling to large size

Transport

- Pedestal physics: understand and control the width and height of the pedestal
  - Develop testable models
  - Develop control techniques, QH–mode, stochastization . . .

Mass Transport

- In-depth understanding of the process contributing to tritium retention, “mass transport”
  - Origin of impurity and fuel particles
    - ★ Erosion; quiescent phase, ELMs
    - ★ Divertor and main chamber recycling
  - Transport channels; closed flux surfaces, open field lines, measure flows

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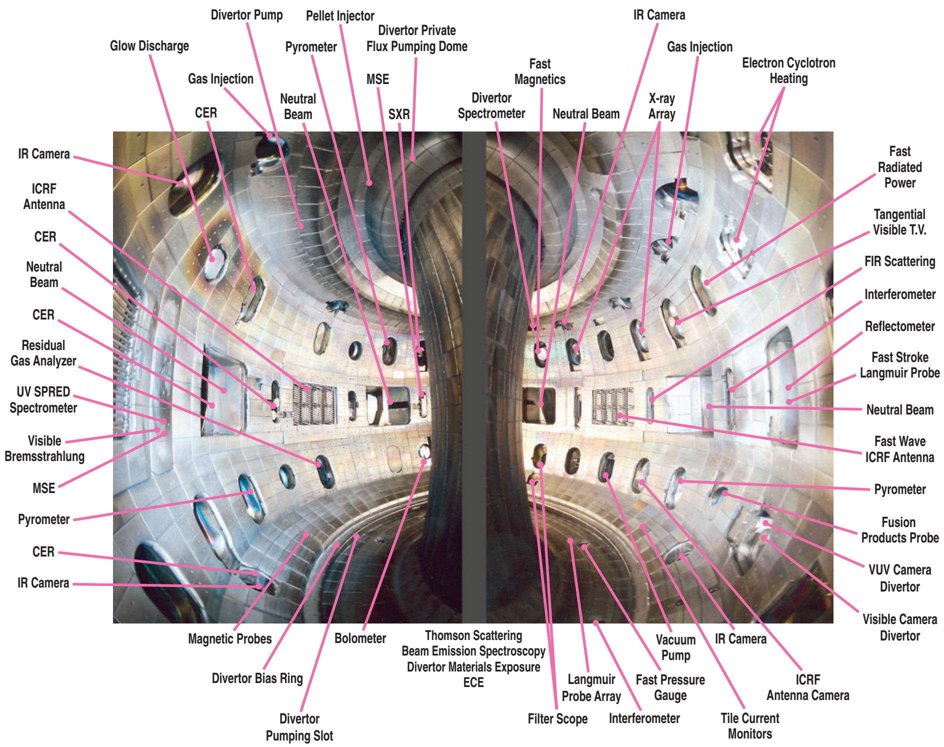
NEW DIAGNOSTICS ARE NEEDED TO ADDRESS KEY PHYSICS CHALLENGES

World Class Diagnostic Set



New Measurements

- Edge J(ρ), lithium beam polarimetry
- Advanced multi-fluid 2-D optical turbulence measurements (Wisc)
  - $\tilde{n}$, $\tilde{v}_r$, $\tilde{v}_\theta$ (BES)
  - $\tilde{T}_i$ (CHERS)
- Enhanced spatial high k-scattering (UCLA)
  - $\tilde{n}$, $10 < k < 40\ \mathrm{cm}^{-1}$, spatially localized
- Phase contrast imaging (MIT)
  - $\tilde{n}$, $k < 100\ \mathrm{cm}^{-1}$
- μ wave backscattering (NM/UCLA)
- Divertor CER (LLNL), T_i, v_i, n_i
- Fast ion profile measurement
- Micro balance surface detectors

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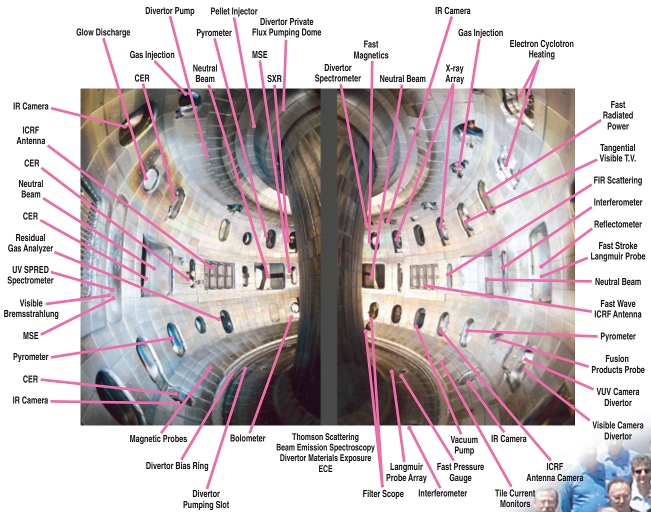
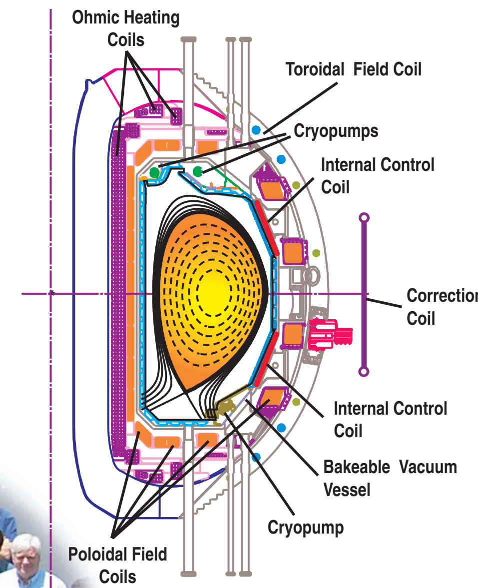
DIII–D WILL CONTINUE TO BE A WORLD CLASS PROGRAM AND FACILITY TO CARRY THE U.S. FORWARD TO BURNING PLASMAS

UNIQUE STRENGTHS

Physics Measurements



Flexibility



International Research Team

Partnerships and Leadership

- Collaborating Exp.
- ITPA
- TTF
- Theory/Modeling
- Burning Plasmas

Plasma Control

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